Jefferson Lab
Thomas Jefferson National Accelerator Facility

Experimental search for a new vector boson A'

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United States Department of Energy

JSA Jefferson Science Associates, LLC

The processes which could have U/A'-boson

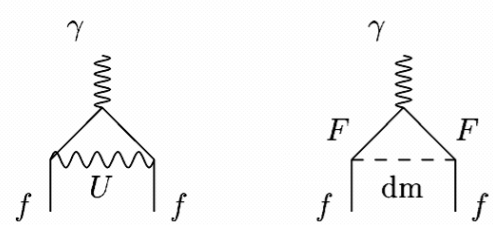
C.Boehm, P.Fayet, Nuclear Physics B 683 (2004)

g_e-2, g_μ-2

π,η decays to $U\gamma$

π,φ,ψ decays to γ + invisible

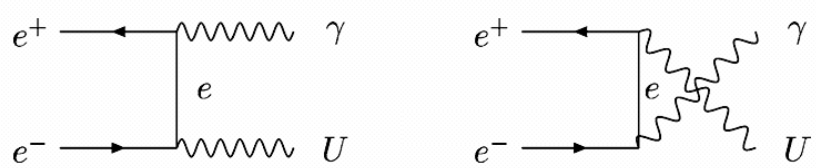
A.4. Constraints from $g-2$



If the U boson mainly decays into dark matter, then the U production process turns out to be of the type $e^+e^- \to \gamma + \not{E}$, where $\not{E}$ is missing energy, which is of interest in experiments searching for single photon production events. But, in the case of a light dark matter candidate, such a process is likely to remain unobserved, owing to the large background associated with $e^+e^- \to \gamma\gamma$, in which one of the two photons escapes detection.

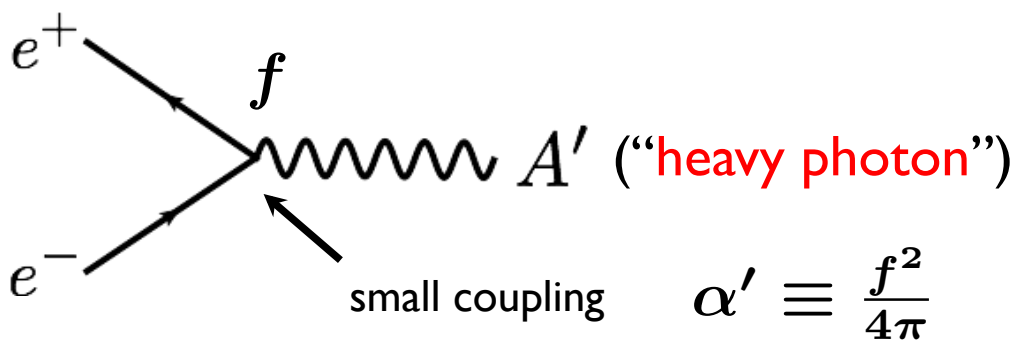
Upper limit for the coupling constant $|f_{eU}|^2 < 2\ 10^{-8}\,(m_U)^2$

A.6.1. Direct U boson production



Why?

Search for new forces mediated by ~100 MeV vector boson A′ with weak coupling to electrons



$$\alpha' \equiv \frac{f^2}{4\pi}$$

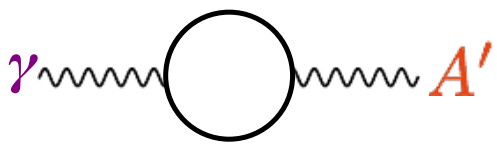
Significant new reach in α' (~2-3 orders of magnitude)
Broad interest in particle physics community

- new gauge force
- dark matter interactions?
- $(g-2)_\mu$ and HyperCP anomalies

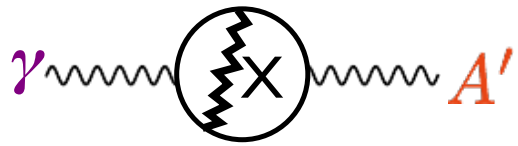
Physics motivation

Weak A' couplings are generic (generated as quantum corrections if **any** heavy particle interacts with γ and A')

[Holdom]



$\epsilon \sim 10^{-4} - 10^{-2}$



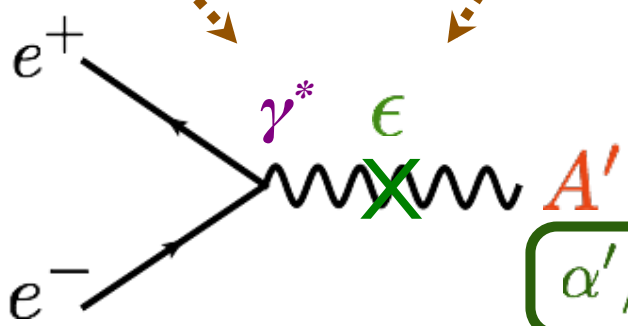
$\epsilon \sim 10^{-5} - 10^{-3}$

(if SM unifies in a GUT)

"kinetic mixing"

$$\left(\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}\right)$$

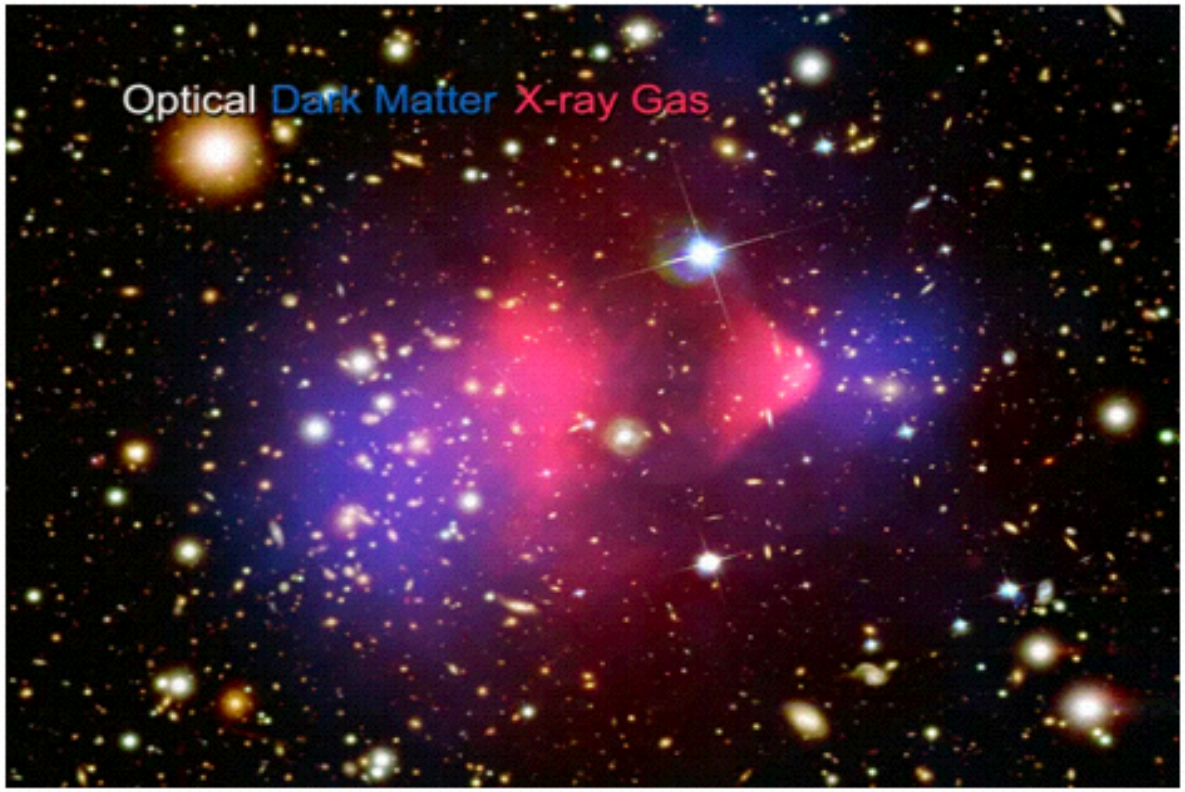
effective coupling:



$$\alpha'/\alpha = \epsilon^2 \sim 10^{-4} - 10^{-10}$$

In simple models: $m_{A'}^2 \sim \epsilon M_W^2 \sim \mathrm{MeV}^2 - \mathrm{GeV}^2$

Physics motivation

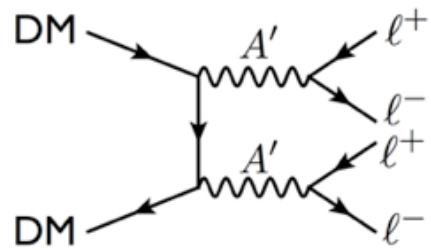


Dark Matter Anomalies – one source ?

1) No antiproton excess observed!
   – not consistent with annihilation into , g ,$W^{\pm}$ Z
   ⇒ new force?
   – suggests $m_{A'} \lesssim 1$ GeV

   ⇒ decay to protons is kinematically forbidden,

   $A' \to \ell^+\ell^-, \pi^+\pi^-$

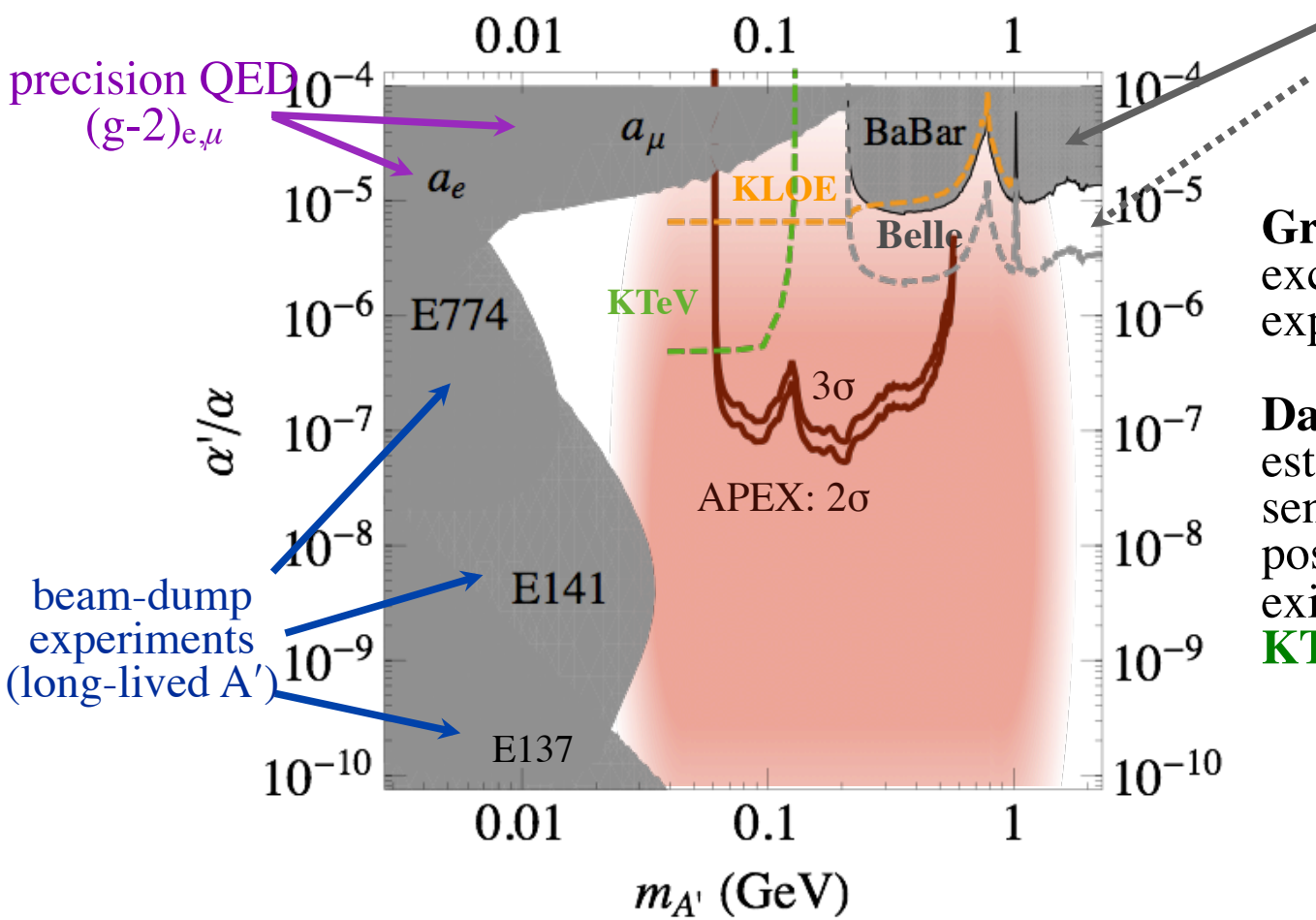


2) Observed annihilation rate is large!
   – consistency with standard cosmology requires attractive force with range ≫ $1/m_{DM}$ ⇒ again suggests $m_{A'} \lesssim 1$ GeV

[Cholis, Goodenough, Weiner;
Arkani-Hamed, Finkbeiner, Slatyer, Weiner;
Pospelov & Ritz]

Irrespective of anomalies: New ~GeV–scale force carriers are important category of physics beyond the Standard Model.
Fixed-target experiments have unique capability to explore this vast territory!

Existing limits and APEX Sensitivity



Gray regions: excluded (2σ) by past experiments

Dashed lines: estimated 2σ sensitivity of other possible searches in existing **KLOE**, **KTeV**, and **Belle** data.

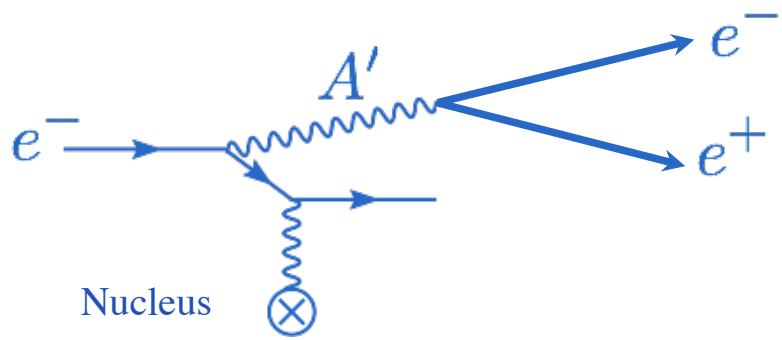
No past experiment has **sufficient statistics and mass resolution** to see A′ if its coupling is below the dotted lines.

This is a theoretically motivated region

– relevant for dark matter – predicted by grand unification

A′ Properties in APEX Search Region ($\alpha'/\alpha > 10^{-7}$)

- Produced abundantly through bremsstrahlung
  (e.g. >1/second for 75 μA beam, 0.1 X_0)



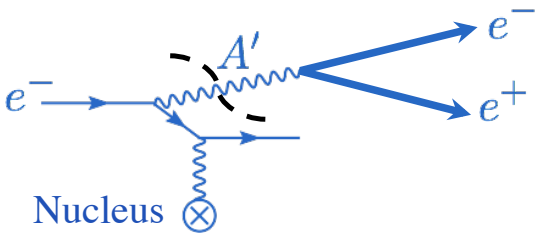
- A′ decays promptly to e^+e^-, $\mu^+\mu^-$, or $\pi^+\pi^-$

  ⇒ large QED background

Strategy: measure e^+e^- mass spectrum precisely, in kinematic region optimized for A′ acceptance and QED background suppression

Approach: A′ Production and Background Kinematics

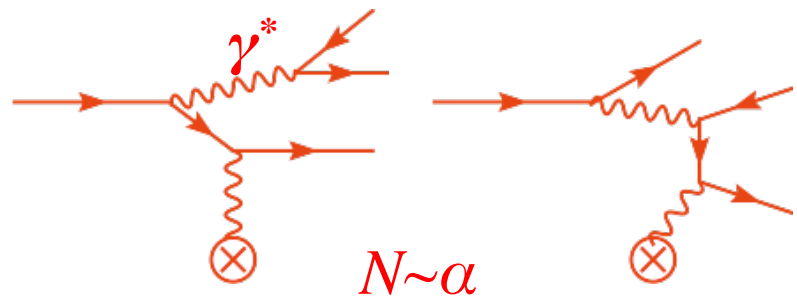
Production diagrams analogous to photon bremsstrahlung



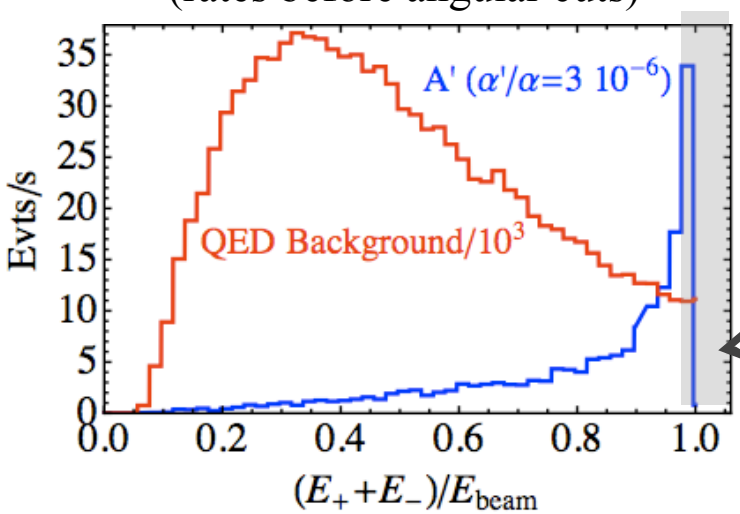
$N \sim \alpha' \times$ branching

→ O(1)

QED Backgrounds



(rates before angular cuts)



A′ products carry full beam energy!

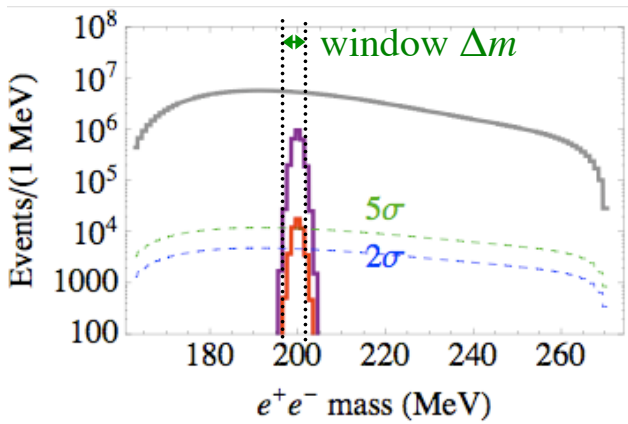
– Distinctive kinematics
– Assists in background suppression

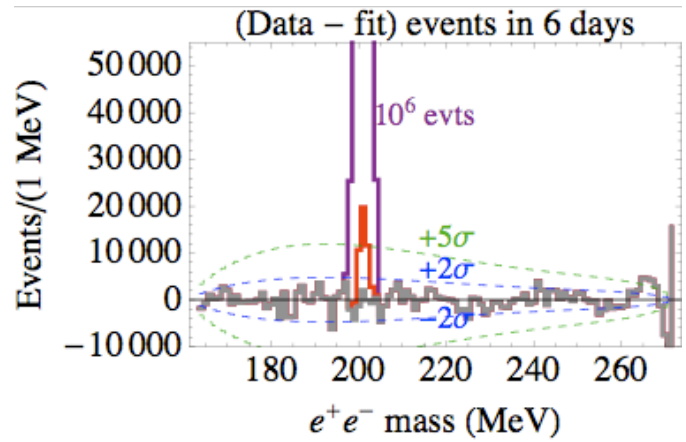
Best kinematics to select events for A′ search

Narrow Resonance Search

To identify A′ signal, must study invariant mass distribution

$$m_{A'} \approx \sqrt{E_+ E_-}(\theta_+ + \theta_-)$$





In mass window Δm:

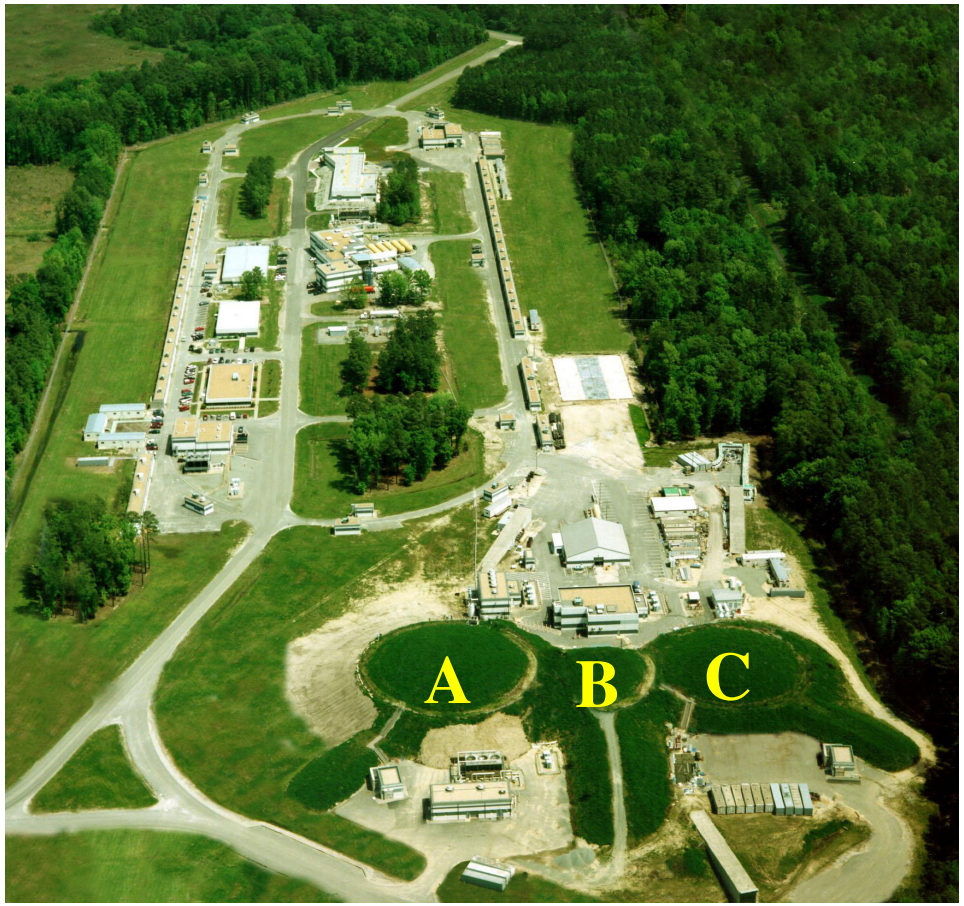
$$\frac{S}{\sqrt{B}} \propto \frac{\alpha'}{\alpha}\sqrt{N_{QED}\left(\frac{m_{A'}}{\Delta m}\right)}$$

To search at small α′, need:

★High e^+e^- statistics

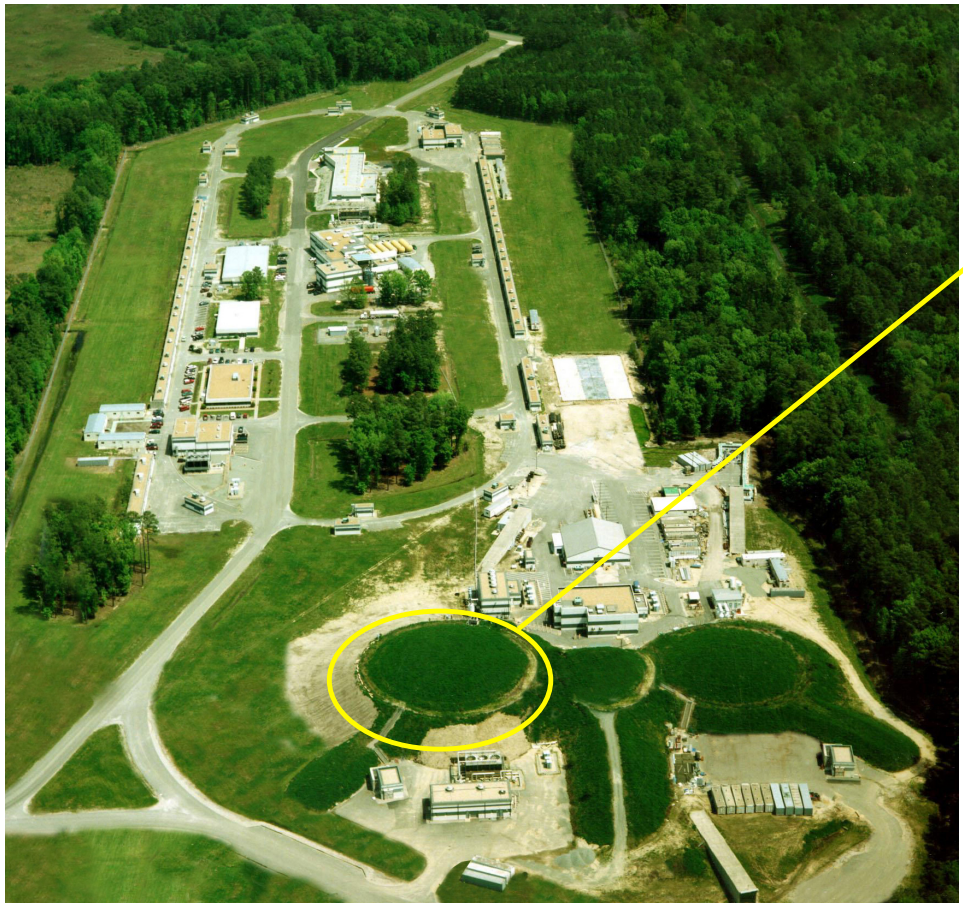
★Excellent mass resolution is a key

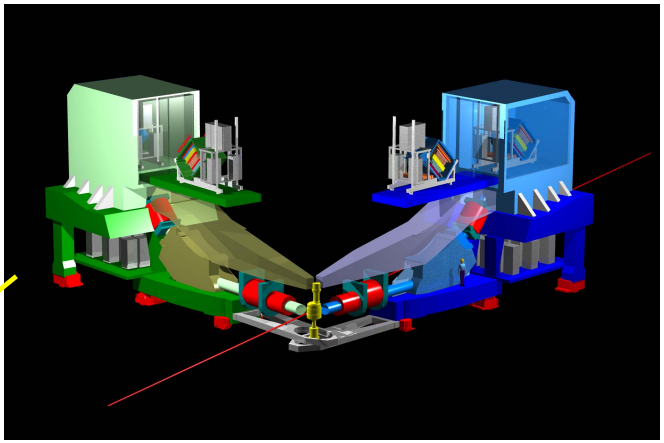
CEBAF Accelerator



Re-circulating linac design
Up to 5 pass, 0.3 to 1.2 GeV per pass.
6.0 GeV max beam energy
100% duty cycle
2ns microstructure
$\sigma_E/E < 1 \cdot 10^{-4}$ (Halls A & C)
Beam polarization up to 85%
180 μA max current

Hall A at Jefferson Lab

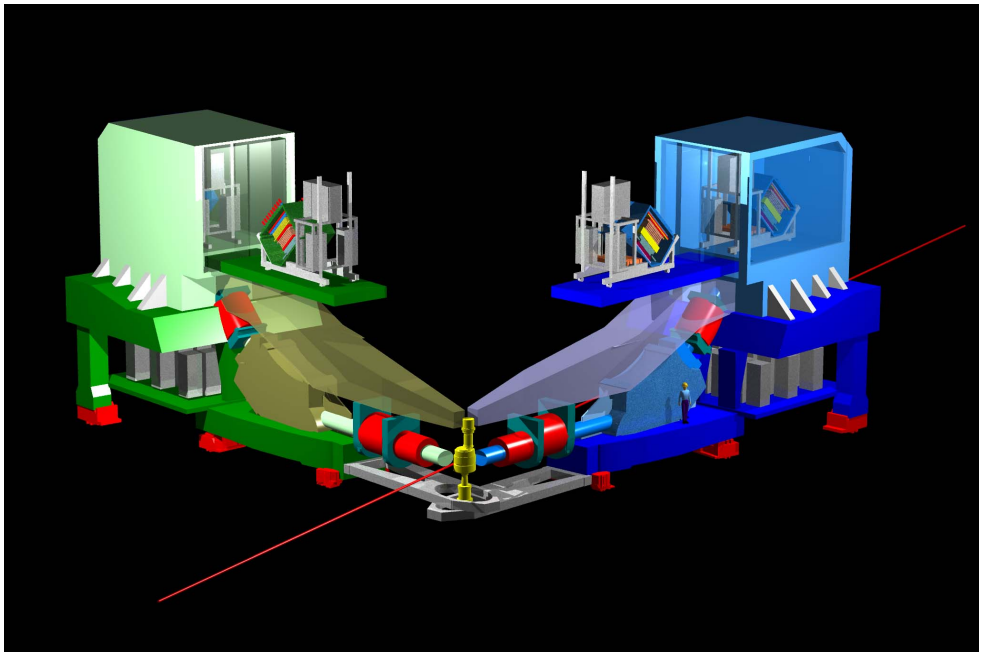




Beamline
$\sigma_E/E < 2 \cdot 10^{-4}$ (absolute)
Non-invasive 3% polarization measurement

Two High Resolution Spectrometers originally designed for (e,e´p) expts.

Hall A at Jefferson Lab

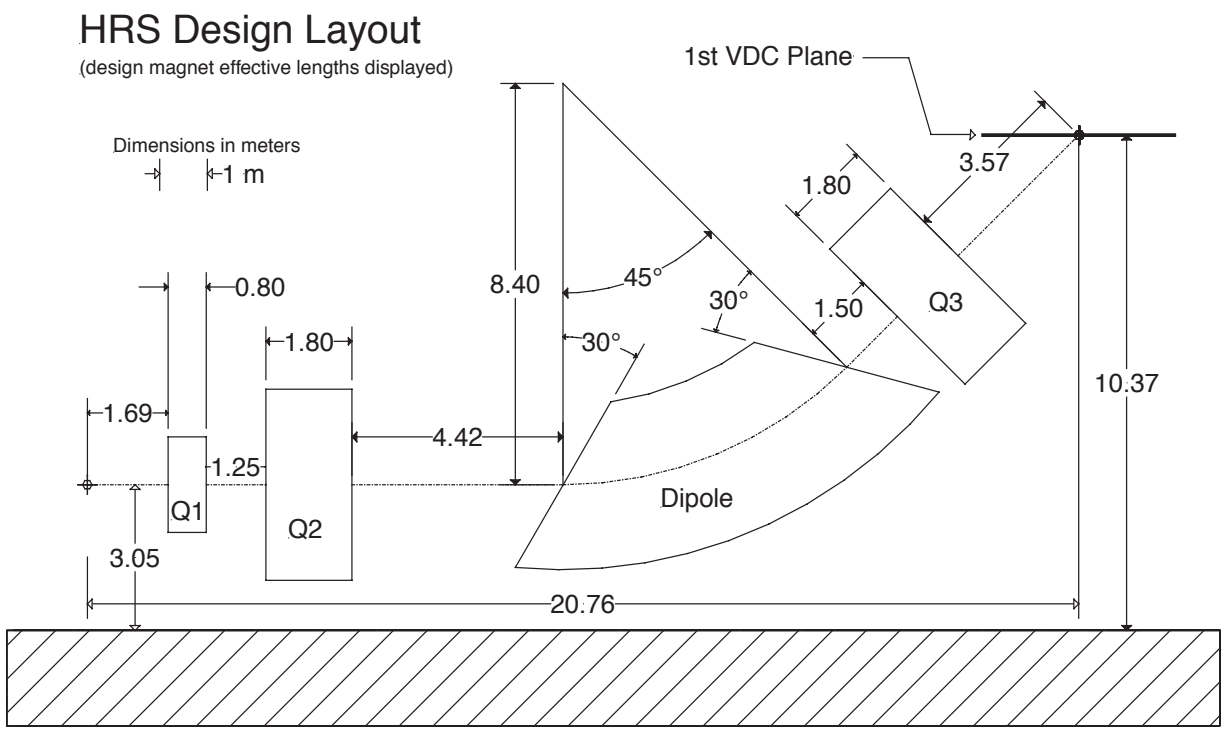


Two HRS Spectrometers
$0.3 < p < 4.0$ GeV/c
$-4.5\% < \Delta p/p < 4.5\%$
6 msr at $12.5° < \theta < 150°$
4.5 msr at $\theta = 6°$ with septum
$-5\text{cm} < \Delta y < 5\text{cm}$

Optics: (FWHM)
$\delta p/p \leq 2 \cdot 10^{-4}$ (achieved)
$\delta\vartheta = 0.5$ mrad, $\delta\varphi = 1$ mrad
$\delta y = 1$mm

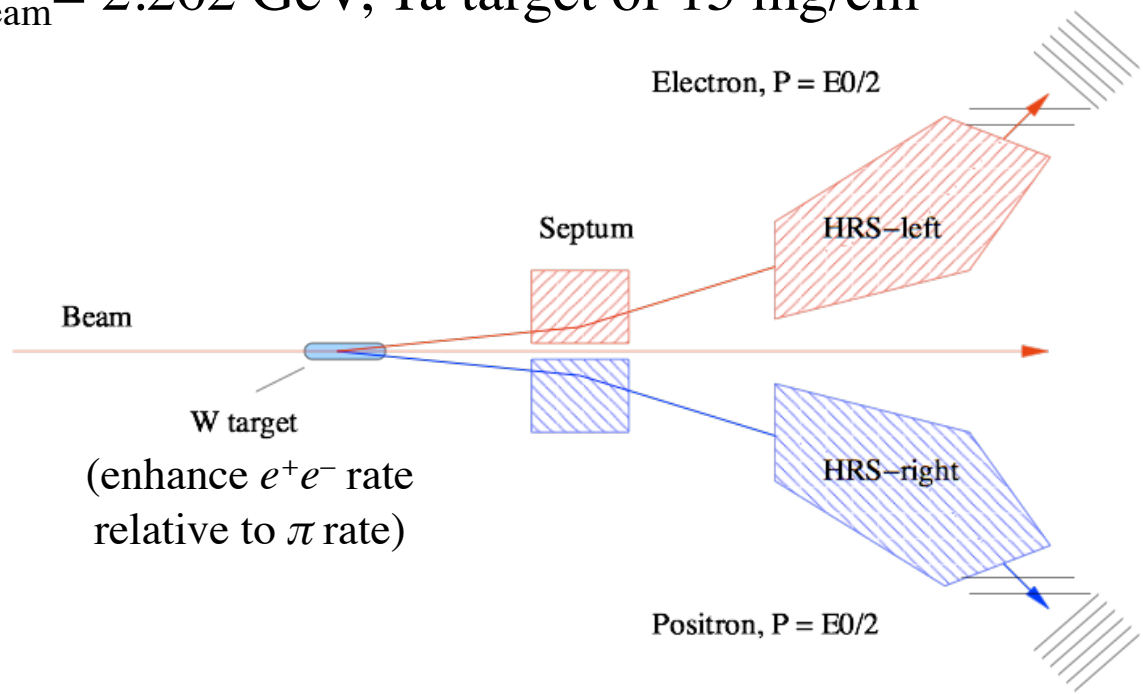
Luminosity ~ 10^{38} cm^{-2}s^{-1}

High Resolution Spectrometer



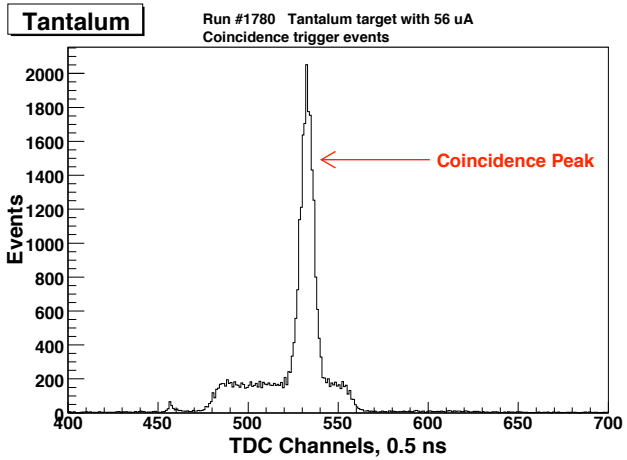
Test Run: June 2010

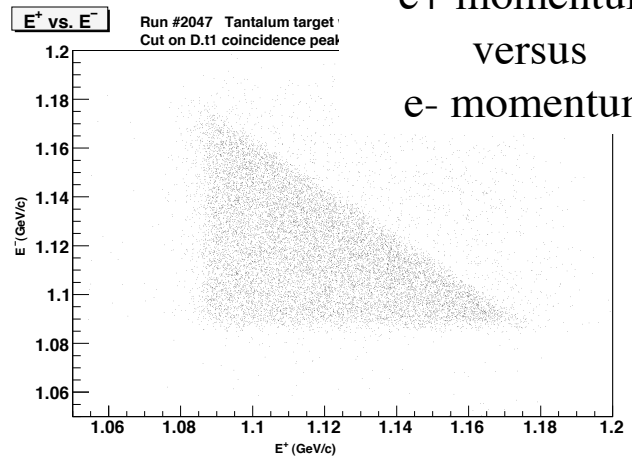
E_{beam}= 2.262 GeV, Ta target of 15 mg/cm^2



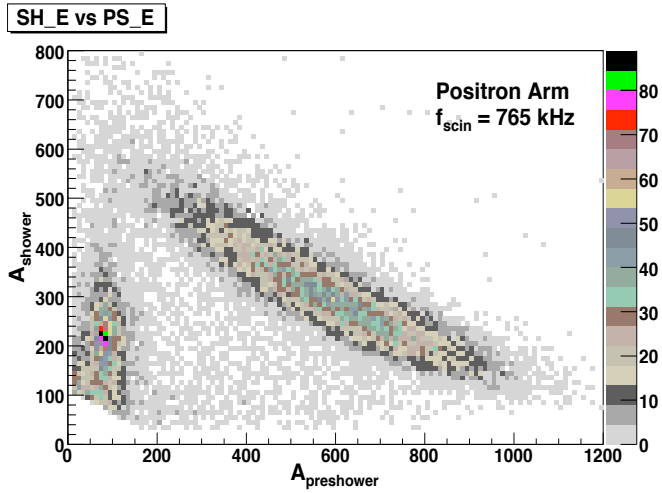
- Signal dominated at $E_+ = E_- = E_{beam}/2$
- Use septa to achieve 5° central angles

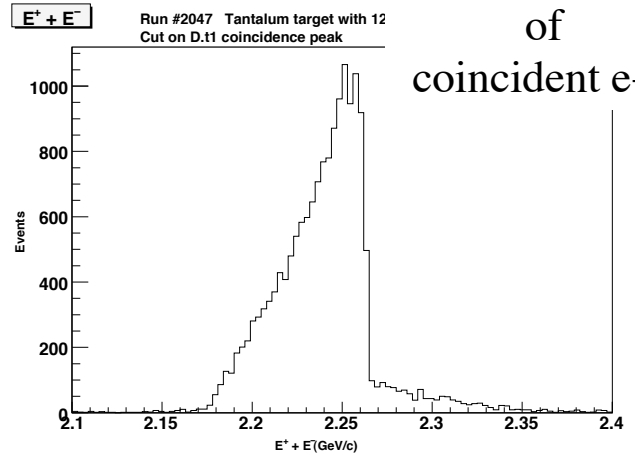
Test Run: June 2010





e+ momentum versus e- momentum

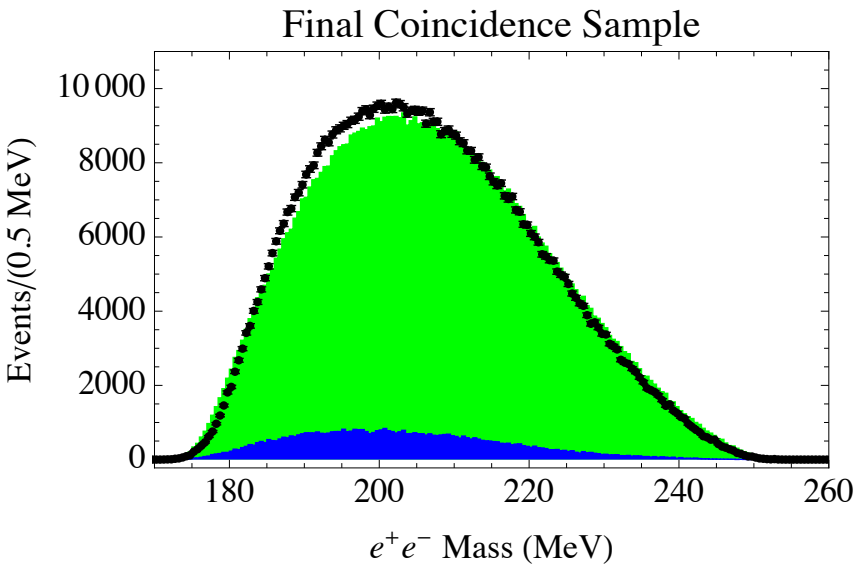


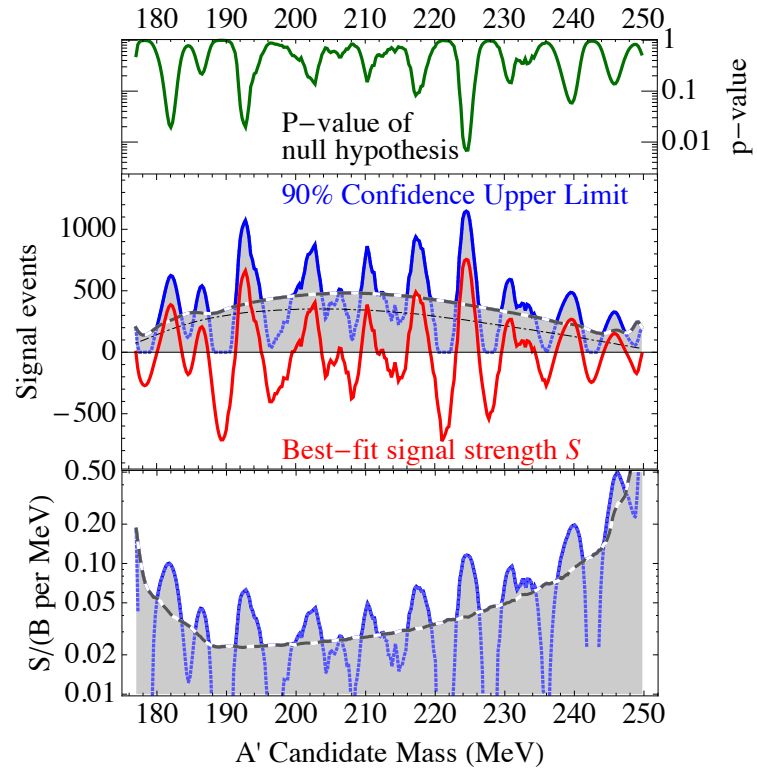


momentum sum of coincident e+e

Test Run Results

The e+e- mass distribution

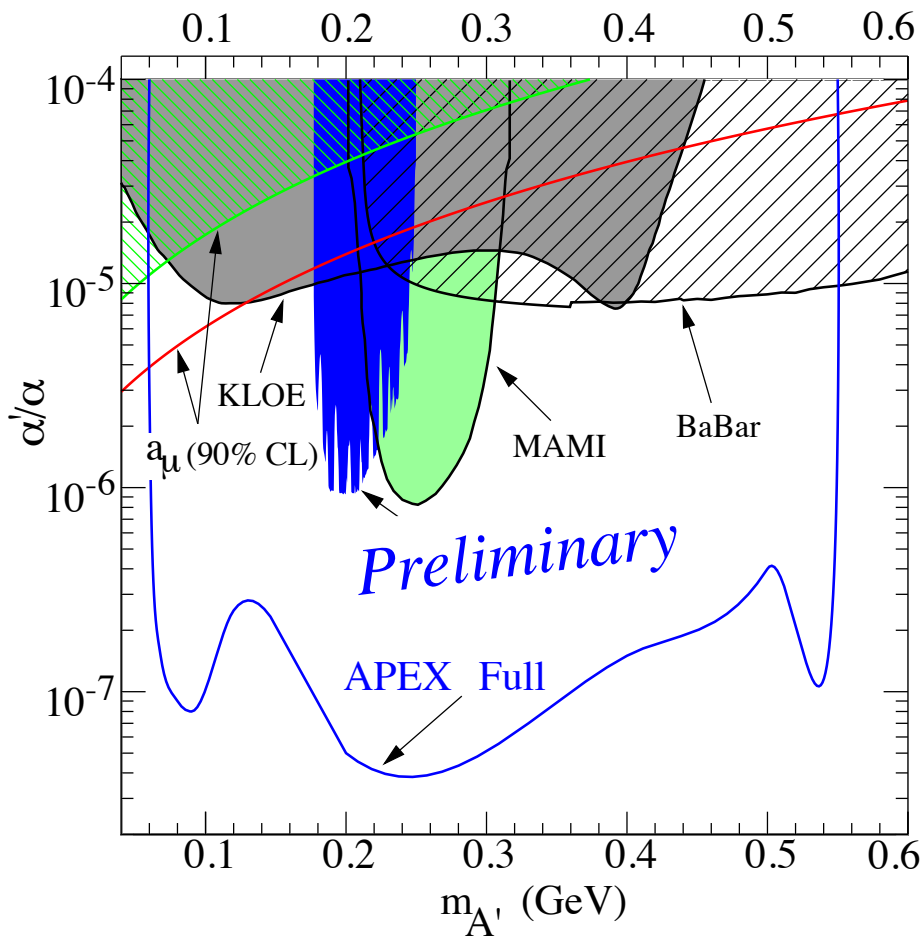




Search for a narrow signal

Test Run Results

APEX test run found no evidence for A'
in the mass range 175-250 MeV with the coupling above ~10^{-6}

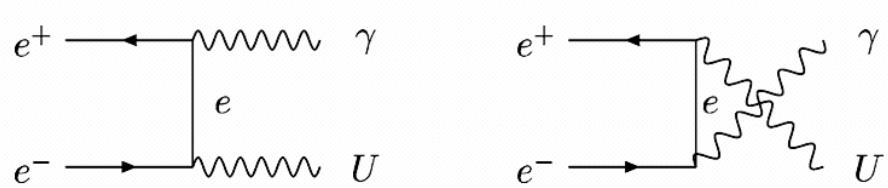


Options for e^+e^- experiment at low s

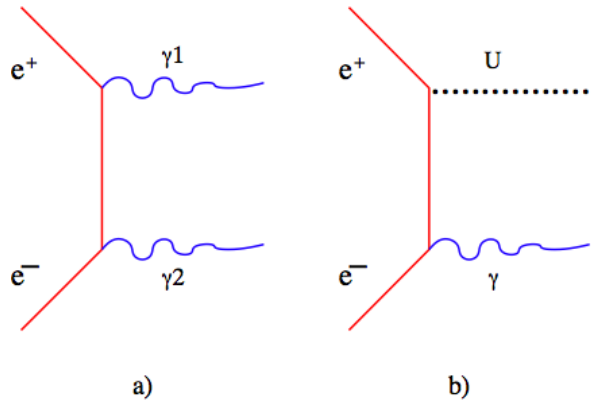
A "very" low energy $s^{1/2} \sim$ 10-30 MeV

a) Search in existing data from good detector =>
   difficult to get resolution at low s
b) 5 MeV x 5 MeV head-head collider of e+e- =>
   problem of very low luminosity
c) Sliding beams of e+e- (200 MeV x 200 MeV)=>
   needs specialized accelerator with two rings
d) Solution is: positron beam and atomic electrons

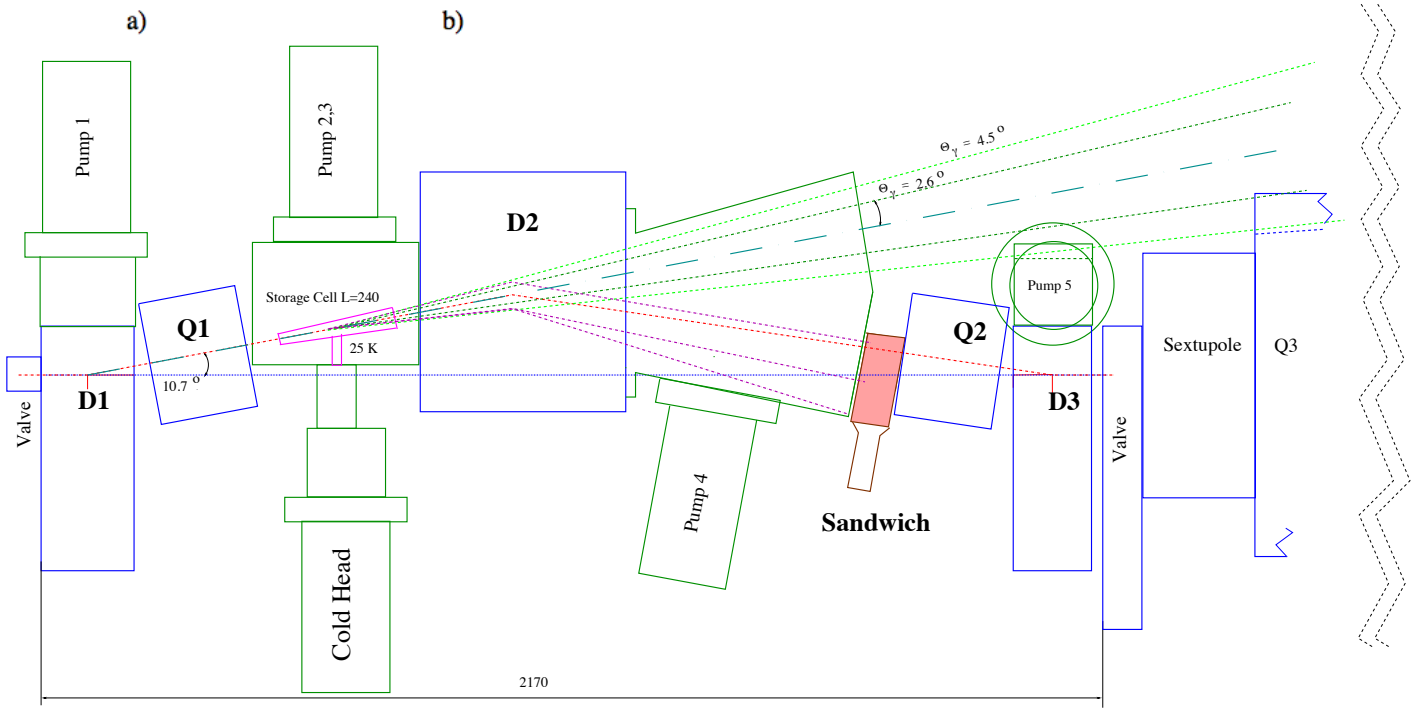
A.6.1. Direct U boson production

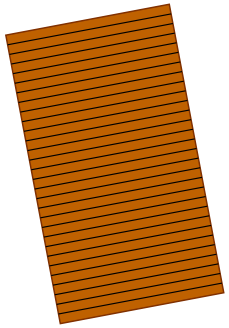


Positron beam on internal Hydrogen target



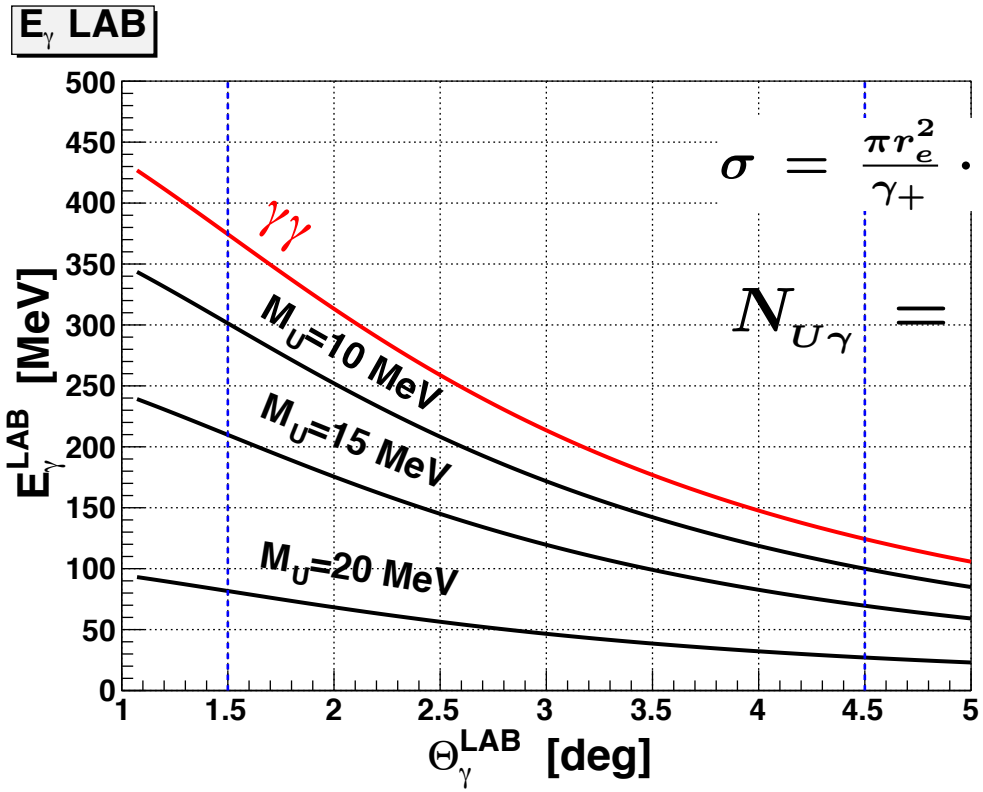
Experiment layout at VEPP-3
(Nikolenko, Rachek, BW)





Photon Detector

Positron beam on internal Hydrogen target



$$\sigma = \frac{\pi r_e^2}{\gamma_+} \cdot (\ln 2\gamma_+ - 1)$$

$$N_{U\gamma} = 2\frac{\alpha'}{\alpha} \cdot N_{\gamma\gamma}$$

Positron beam on internal Hydrogen target